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Establishment of Process model for rapid prototyping technique (Stereolithography) to enhance the part quality by Taguchi method

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Abstract

Rapid prototyping (RP) has evolved as frontier technology in the recent times, which allows direct transformation of CAD files into functional prototypes where it tremendously reduces the lead-time to produce physical prototypes necessary for design verification, fit and functional analysis by generating the prototypes directly from the CAD data. Part quality in the rapid prototyping process is a function of build parameters such as hatch cure depth, layer thickness, orientation, hatch file, hatch spacing and part characteristics. Thus an attempt was made to identify study and optimize the process parameters governing the system which are related to part characteristics using Taguchi experimental design techniques-quality.

The part characteristics can be divided into part physical characteristics and mechanical characteristics. The physical characteristics are surface finish, dimensional accuracy, distortion, layer thickness, hatch cure, and hatch file whereas, mechanical characteristics are flexural strength, ultimate tensile strength and impact strength. Thus, the paper proposes to characterize the influence of the physical build parameters over the part quality. An orthogonal array of experiment was developed which has the least number of experimental runs with desired process parameter settings and also by analysis tools such as ANOVA (Analysis of Variance). Establishment of experimentally verified correlations between the physical part characteristics and mechanical part characteristics to obtain an optimal process parameter level for betterment of part quality is obtained. The process model obtained by the empirical relation can be used to determine the strength of the prototype for the given set of parameters that shows the dependency of strength, which are essential for designers and RP machine users.

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1. Introduction

Due to the advances in electronics and computers, there has been a significant growth in communication, information technology and worldwide networking, which leads to globalization and opening of markets [1, 2]. Thus in product development, rapid prototyping (RP) and rapid product development have turned out to be the key instruments to save time and money with respect to the development of innovative products [2,3]. Stereolithography (SLA) is one of the RP techniques, which involve fabrication of intricate shape of a plastic monomer directly from Computer aided design (CAD) data by depositing material layer by layer by photo polymerization process [4]. The SLA process involves the following steps; creation of the CAD model of the design; conversion of the CAD model to the standard triangulation language (STL) file format; slice the STL file into thin cross sectional layers; constructing the model one layer a top another; clean and finish off the model. SLA prototypes have wide application in aerospace, automobile, and manufacturing sectors especially in rapid tooling. Strength plays a very important role in rapid tooling [5] where the components have to withstand high pressure during the test of fitment and also when used as a die in injection moulding, where the dies prepared through SLA process will be subjected to high tension due to high injection pressure. Hence, an attempt is made in order to achieve high strength of the prototypes with the specified process parameters which gives prior information of the part strength before fabricating the actual SLA prototypes. Hence, parameter optimization of SLA process is investigated and evaluated through a standard test specimen [6, 7].

Nomenclature

RV	Response variable , i	process parameter identifier , ϵ	Error component
β_0	constant coefficient , β_{1i}	Linear Coefficient for the i^{th} parameter , n	number of replication,
β_{2i}	Non linear coefficient for the i^{th} parameter,	S/N ratio , y_i	the i^{th} result of the experiment,
$P_{1(i)}$	1 st order orthogonal polynomial of the parameter , $P_{2(i)}$	2 nd order orthogonal polynomial of the parameter,	
L_t	Layer thickness , O	Orientation , H_s	Hatch space

2. The Experimental Methods and Methodology

The experimental building material adopted is CIBATOOL 5530 epoxy resin. The experimental building models are categorized into three specimens viz: the tensile test, flexural test and impact test which are characterized using ASTM D638-01 [8], ASTM D790-03 [9] and ASTM D256-04 [10] specifications respectively. The STL format is generated by CATIA V5 R16 and sent to the 3D system SLA 5000 rapid prototyping machine. The various conditions in pre-processing steps such as STL verification, deposition layer thickness, orientation, building interior structure form, supporting method and building deposition direction are incorporated by means of 3D light year software [11] provided by 3D system of Valencia, USA followed by the layer slicing process to generate the building path with ACESTM build style. Building quality characteristics or attributes include the larger-the-better (LB) for the strength of the SLA prototypes.

2.1 Experimental apparatus

The major experimental apparatus adopted includes, 3D system SLA5000 rapid prototyping machine produced by the Valencia, USA where it uses CIBATOOL 5530 epoxy resin to build geometrical shape of the work piece by photo polymerization process. Similarly, the tensile and flexural tests were conducted using Instron Universal Testing Machine, UK make, Model 5582. The impact test was conducted using impact tester, Aditya Instruments, Bangalore, Model IT-30.

2.2 Taguchi Quality Engineering

The orthogonal array is employed for the Taguchi method as the experimental analysis basis. The experimental factors and their corresponding levels are identified. Then the experimental results are manipulated

and validated by analysis of variance (ANOVA), in order to determine each factor effect versus the response variable-strength of the SLA prototypes. The experimental procedures is as given below: Identification of SLA process parameter that influence the response variable, determining the various levels of the factors, Based on the factors and their levels, the degree of freedom is calculated and the suitable orthogonal array is selected, the experiment proceeds according to the variable factor layout of the orthogonal array. The experimental results are obtained and the signal to noise ratio (S/N ratio), the ANOVA and the corresponding contribution are computed, establishment of empirical relationship for the response variable under different parameter settings.

The Taguchi method, parameter design converts the objective value to S/N ratio, which is known as quality characteristic evaluation index [12, 13, 14], with the S/N ratio where the least variation and the optimal quality design can be obtained. The S/N ratio is beneficial in increasing factor weighting effect, decreasing mutual action, simultaneously processing the average and variation and improving the quality. The higher the S/N ratio, the more stable quality can be obtained. According to the response variable, larger the better (LB) is used. The LB: the objective optimal value is larger better for the strength of the SLA prototypes.

Figure 1 shows the probable parameters (Causes) that influence the part quality characteristics (effects) in the SLA Process. Fig 2 represents the various process parameters of SLA Process, among these the layer thickness (Lt): the thickness where the model is sliced in the Z direction, Orientation (O): position in which the prototype is build and Hatch Spacing (H_s): narrow region solidified by the laser scanning. If the strand is located at the top or bottom surface of part, spacing is called fill spacing otherwise hatch spacing, these are the parameters which influences the strength of the SLA parts [15]. The Table 1 provides the three levels of the process parameters for the experimentation. The total number of experiments in full factorial design for “m” parameters each set of “L” levels is L^m and it increases exponentially with L & m. Taguchi suggested the use of orthogonal array which will be used for conducting the fractional factorial experiments [16]. The Taguchi orthogonal array adopted in the research experiment is L_9 for three factors-three level settings as shown in table 2.

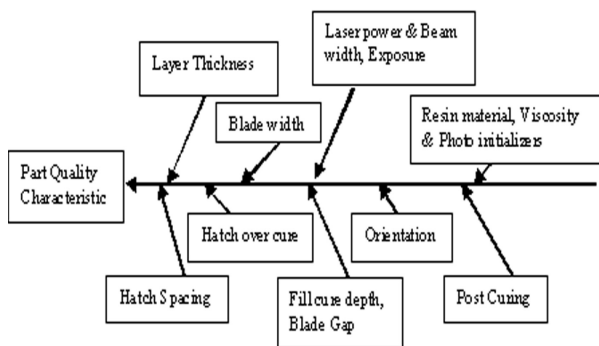


Figure 1: Cause & effect diagram of SLA process Parameters.

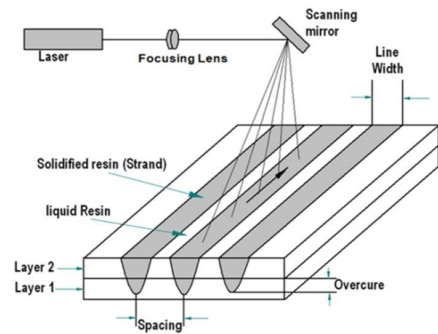


Figure 2: Process parameter in SLA process

Table 1: Description of experimental control parameters

Symbol	Control Parameter	LEVEL 1	LEVEL 2	LEVEL 3
A	Layer Thickness(L_t)	0.075	0.1	0.125
B	Orientations (O)	0° (H_x)	45° (VH_{xy})	90° (V_y)
C	Hatch Spacing (H_s)	0.01	0.015	0.02

Table 2: L₉ Orthogonal array

Experimental run (i)	LEVELS		
	A-Layer Thickness(L _t)- mm	B-Orientation (O)- °	C-Hatch Spacing (H _s) mm
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

3. Experimentation

3.1 Experimental analysis for tensile strength (Ts)

The nine tensile specimens as per the ASTM standards (ASTM D638-01) were built for L₉ orthogonal array setting using epoxy resin CIBATOOL SL5530 in SL5000 machine of three replications each. The dimensional details of the test specimen were built as per ASTM standards [8] and the SLA prototypes are as shown in Fig 3. The tensile strength is calculated using the ratio of ultimate load to cross sectional area. The experimental results are given in Table 3.

Table 3: Ultimate tensile strength for OA settings

j	1	2	3	4	5	6	7	8	9
T _s (N/mm ²)	55.46	54.57	55.07	58.46	54.51	58.59	58.62	55.34	61.73



Fig 3: SLA prototypes of tensile test specimen

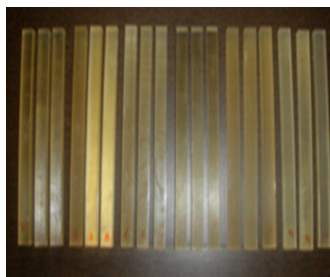


Fig 5: SLA prototypes of Flexural test specimen



Fig 7: SLA prototypes of Impact test specimen

3.1.1 Prediction of optimal levels of process parameters

S/N ratio is an evaluation measure for the process parameters at each of their process level where the signal represents the desirable target (LB of tensile strength) and noise indicates the undesirable value which is defined in equation 1. The average S/N ratio for each process parameter (control variable) at each level is an average of n_j at a defined level. Table 4 provides the average S/N ratios for the process parameters (L_t, O & H_s) at the three levels. The graph represented in Fig 4 shows the variation of average S/N ratio with respect to the various levels. The main objective is to maximize the tensile strength of the parts produced by SLA process, in order to achieve this S/N ratio should be more. Hence, the level having higher S/N ratio is selected as the optimum level, which are contributing higher strength to the part.

Therefore, the optimum levels contributing to the higher strength of the part are

Layer thickness : 0.125mm (Level 3, S/N Ratio: **35.34**) Orientation : 90° V_y (Level 3, S/N Ratio: **35.33**)
 Hatch Spacing : 0.015 (Level 2, S/N Ratio: **35.29**)

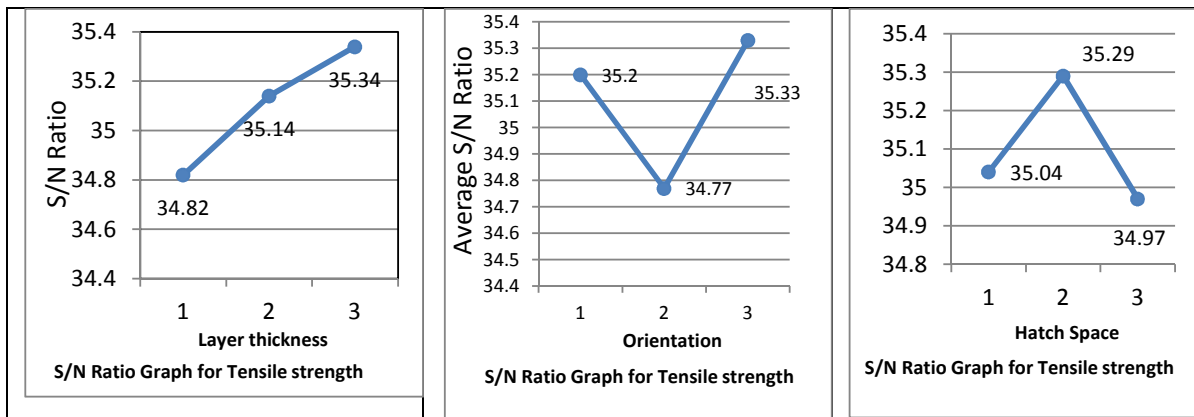


Fig 4: S/N ratio graph for tensile strength Analysis

Table 4: S/N Ratio for different level for TS

Parameters	LEVEL	n_{avg}
Layer Thickness	1	34.82
	2	35.14
	3	35.34
Orientation	1	35.2
	2	34.77
	3	35.33
Hatch Spacing	1	35.04
	2	35.29
	3	34.97

Table 5: Shows the % of contribution of the parameters to the tensile strength along with the estimated ANOVA parameter.

Parameter "i"	Sum of Squares	Degree of freedom	Mean sum of squares	F Statistic	F tabulated $F_{(0.1,2,2)}$	% of contrib ^a
L_t	18.57	2	9.285	9.622*		36.93
O	21.72	2	10.86	11.25*	9	43.19
H_s	8.06	2	4.03	4.176		16.03
Error	1.93	2	0.965			3.83
Total	50.28	8	25.14			

*Significance at 90% confidence Level (F Statistics > F Tabulated)

3.1.2 Identification of significant and percentage of contribution of process parameters

The process parameter (L_t , O & H_s) which influences much on response variable is identified through the percentage of contribution of each parameter. The parameter which has more percentage of contribution is the significant parameter to the response variable [17, 18, 19, 20] have mentioned ANOVA is widely used for determining the significance of the independent variables in influencing the dependent variables and also in determination of percentage of contribution of these dependent variables to the response variable.

Table 5 shows the percentage of contribution of the parameters to the response variable with the ANOVA parameters. Hence, from the ANOVA table the significance of each parameter is identified.

3.2 Experimental Analysis for Flexural Strength (Fs)

The analysis carried out for the flexural strength is identical to the one in section 3.1. The nine flexural test specimen as per the ASTM standards (ASTM D790-03) were built for L_9 orthogonal array setting using epoxy resin CIBATOOL SL5530 in SL5000 machine of three replications each. The dimensional details of the test specimen were built as per ASTM standards [9] and the SLA prototypes are as shown in Fig 5. The flexural specimens are subjected to point load at the midpoint between the supports, which are placed at 190mm apart with a particular load where the fatigue occurs. The flexural strength at fracture (δ) is determined by the following equation 2.

$$\delta = \frac{W}{L} \left(\frac{1}{b} - \frac{1}{d} \right) \quad (1)$$

Where W is load in Newton, L is the length of the test specimen in mm, b is the breadth of the test specimen in mm, d is the depth of the test specimen in mm. The experimental results are tabulated in table 6 which shows the flexural strength. Table 7 shows the S/N ratio for each of the level in each factor and fig 6 shows the variation of S/N ratio for all the controllable factors. The level which have higher S/N ratio is selected as the optimum level contributing higher flexural strength to the part. Hence the optimal parameters are Layer thickness: 0.125mm (Level 3, S/N Ratio: **41.32**), Orientation: $90^\circ V_y$ (Level 3, S/N Ratio: **41.3**) Hatch Spacing: 0.015 (Level 2, S/N Ratio: **41.29**).

The Table 8 represents the percentage of contribution of each factor for flexural strength along with the estimated ANOVA parameters. From the ANOVA table the significance of each parameter is identified.

Table 6: Flexural strength for OA Settings

j exp., run	1	2	3	4	5	6	7	8	9
$FS_j(N/mm^2)$	116.67	113.92	114.08	115.7	110.0	115.6	115.8	114.8	118.7

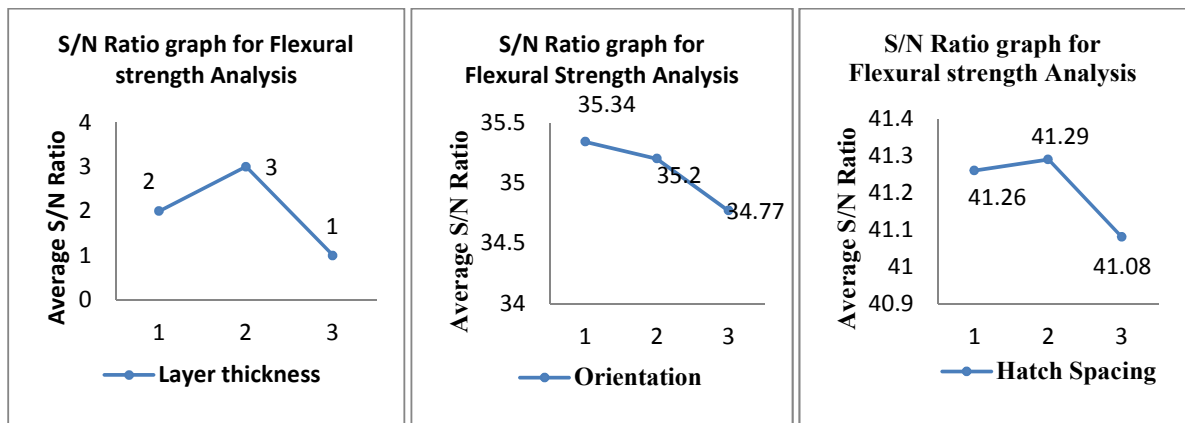


Fig 6: S/N ratio graph for Flexural strength Analysis

Table 7: S/N Ratio for different level for FS

Parameters	LEVEL	η_{avg}
Layer Thickness	1	41.2
	2	41.11
	3	41.32
Orientation	1	41.28
	2	41.05
	3	41.3
Hatch Spacing	1	41.26
	2	41.29
	3	41.08

Table 8: Shows the % of contribution of the parameters to the Flexural strength along with the estimated ANOVA parameter.

Parameter "i"	Sum of Squares	Degree of freedom	Mean sum of squares	F Statistics	F tabulated $F_{(0.1,2,2)}$	% of contrib ⁿ
L_t	10.75	2	5.375	82.69		23.88
O	20.3	2	10.15	156.15*	99	45.09
H_s	13.84	2	6.92	106.45*		30.75
Error	0.13	2	0.065			0.28
Total	45.02	8	22.507			

* Significance at 99% confidence Level (F Statistics > F Tabulated)

Table 9: Impact strength for OA setting

j exp., run	1	2	3	4	5	6	7	8	9
$IS_j (J/m)$	20.72	22	21.1	20.3	17.9	21.3	21.4	19	23.6

3.3 Experimental analysis for impact strength

The analysis carried out for the impact strength is identical to the one in section 3.1. The nine impact test specimen as per the ASTM standards (ASTM D256-04) are built for L_9 orthogonal array setting using epoxy resin CIBATOOL SL5530 in SL5000 machine of three replications each. The dimensional details of the test specimen were built as per ASTM standards [10] and the SLA prototypes are shown in Fig 7. In Izod test method, the specimen placed vertically and is broken by a single swing of the pendulum weight with a contact point at a fixed distance from the centreline of the notch. The impact strength obtained through the ratio of energy absorbed by the specimen during the break and the width of the specimen using izod impact tests. The experimental results of impact strength are tabulated in table 9. Table 10 shows the S/N ratio for each of the level in each factor and Fig 8 shows the variation of S/N ratio for all the controllable factors. The level which have higher S/N ratio is selected as the optimum level contributing higher Impact strength to the part. Hence the optimal parameters are Layer thickness : 0.125mm (Level 3, S/N Ratio: **26.68**), Orientation: $90^\circ V_y$ (Level 3, S/N Ratio: **26.84**), Hatch Spacing: 0.015 (Level 2, S/N Ratio: **26.82**). The table 11 represents the percentage of contribution of each factor for Impact strength along with the estimated ANOVA parameters. From the ANOVA table the significance of each parameter is identified.

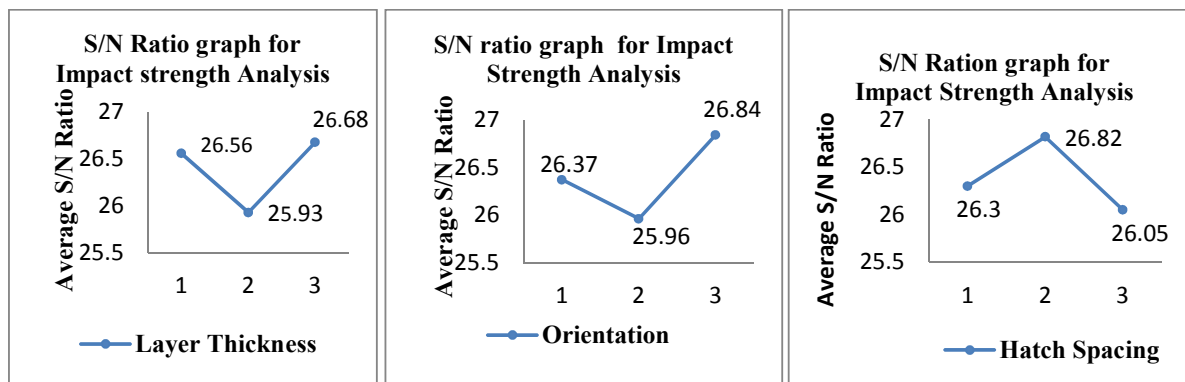


Fig 8: S/N ratio graph for Impact strength Analysis

Table 10: S/N Ratio for different level for IS

Parameters	LEVEL	n_{avg}
Layer Thickness	1	26.56
	2	25.93
	3	26.68
Orientation	1	26.37
	2	25.96
	3	26.84
Hatch Spacing	1	26.3
	2	26.82
	3	26.05

Table 11: Shows the % of contribution of the parameters to the Impact strength along with the estimated ANOVA parameter.

Parameter "i"	Sum of Squares	Degree of freedom	Mean sum of squares	F Statistics	F tabulated $F_{(0.1,2,2)}$	% of contrib ^a
L_t	5.5	2	2.75	2.69		28.47
O	6.44	2	3.22	3.16*	3	33.33
H_s	5.34	2	2.67	2.617		27.64
Error	2.04	2	1.02			10.55
Total	19.32	8	9.66			

* Significance at 75% confidence Level (F Statistics > F Tabulated)

4. Establishment of Process model (Regression equation)

ANOVA reveals that the layer thickness, orientation, and hatch spacing are contributing significantly to mechanical properties. Hence, establishment of a process model (empirical relationship / regression model) for mechanical properties (tensile/flexural/impact strength) as a function of process parameters (layer thickness,

orientation and hatch spacing) is used to predict the strength for the given set of process parameters, which provides the prior information of the strength before fabricating the SLA prototype and useful for rapid designers as well as RP machine users. Montgomery [16] suggests the orthogonal polynomial which is very much useful for developing the process model with the L_9 Orthogonal data. A Quadratic polynomial model is proposed to establish the process model between the response variable and process parameter as shown in equation 3.

$$= + () + () + ()$$

4.1 Empirical relation for tensile strength versus process parameters

Layer thickness, Orientation and Hatch spacing which influences the tensile strength, the response variable. The regression equation for the tensile strength is as given by equation 4.

Among the above process parameters, layer thickness and hatch Space are quantitative measures with equal spacing and orientation is a qualitative measures. Hence the coded value of the orthogonal array is used with two extremes and the center value i.e., lower, higher and middle value which are coded as -1, 0, 1 respectively [21, 22].

$$\begin{aligned} () = & + * \text{---} + * \frac{()}{\text{---}} - \text{---} + * \\ & \text{---} + * \frac{()}{\text{---}} - \text{---} + * \text{---} + * \\ & \frac{()}{\text{---}} - \text{---} \end{aligned} \quad (\text{Eq 4})$$

The table 12 provides the values of orthogonal contrast coefficient for linear and non-linear term. Hence, the mean value of the levels of process parameters () becomes zero and the spacing between the levels of process parameters (d_i) become one. Therefore, the study with three parameter will have $\lambda_1 = 1$ and $\lambda_2 = 3$ [16]. Substituting the value of (), d_i , λ_1 , λ_2 and by using the coded value of the orthogonal contrast coefficients for linear and non linear the constant and coefficients with respect to the various process parameters are found out and the process model (Empirical relation) is given in equation 5.

$$= - . + . + . + . - . - . + . \quad (\text{Eq 5})$$

Table 12: Orthogonal contrast coefficients for linear and Non-linear at different levels

LEVELS	LINEAR	NON LINEAR
Lower	-1	1
Medium	0	-2
Higher	1	1

4.2 Empirical relation for Flexural strength versus process parameters

Similarly the process model is established between flexural strength versus process parameter (L_t , O and H_s) as in section 4.1 is given in equation 6.

$$= . + . + . + . - . - . + . ()$$

4.3 Empirical relation for Impact strength versus process parameters

In the similar manner the process model is established between Impact strength versus process parameter (L_t , O and H_s) as in section 4.1 is given in equation 7.

$$= . + . + . + . - . - . + . ()$$

5. Conclusions

Optimizing the rapid prototyping SLA process by using Taguchi method is proposed. In this paper, an attempt is made to analyze the process parameters that influence the strength aspect of the SLA parts which are useful for various applications of the prototypes in testing and tooling process. The major conclusions are as follows:

- The parameters L_t , O and H_s influences much on part strength of SLA prototypes.
- The optimal level combination of the process parameters are: Layer Thickness: 0.125mm (Level 3), Orientation: 90° - V_y (Level 3), Hatch Spacing : 0.015 (Level 2) for tensile, flexural and Impact strength of the SLA prototypes.
- Among the three process parameters the L_t and O are major contributing parameter for the tensile strength, O and H_s are major contributing parameter for the flexural strength and O has more significance among the parameters for the impact strength.
- The empirical relationship (Process model) between the part strength characteristics and the influencing parameters has been established for stereolithography process, which can predict the strength of the SLA prototypes by prior knowledge of part strength before building the prototypes.

The procedure is applied in order to optimize the other rapid prototyping process with different materials. The optimization is done by factorial design (Taguchi technique) to know the effect of parameter on the variables which can be determined by integrating the Taguchi method with grey relational analysis where the optimal parameter combinations of the multiple quality characteristics. The process model may be further refined by using non-classical optimization techniques such as genetic algorithm and neural networks.

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